Depository

IC bureau of mines information circular 7999

OHIO STATE UNIVERSITY
APR 24 1961
LIB.

RESEARCH AND TECHNOLOGIC WORK ON EXPLOSIVES, EXPLOSIONS, AND FLAMES, FISCAL YEARS 1957 AND 1958

By Ruth F. Brinkley and R. W. Van Dolah

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
(1961)

Generated on 2024-09-22 03:09 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

This publication has been cataloged as follows:

Brinkley, Ruth Frank.

Research and technologic work on explosives, explosions, and flames: fiscal years 1957 and 1958, by Ruth F. Brinkley and Robert W. Van Dolah. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1961]

ii, 30 p. illus. 26 cm. (U.S. Bureau of Mines. Information circular 7999)

Title varies; 1953 and 1954, Report of research and technologic work on explosives...

Bibliographical footnotes.

1. Explosives - Testing. 2. Combustion. 3. Dust explosion. 4. Coal mines and mining - Explosives. I. Van Dolah, Robert Wayne, joint author. (Series)

TN23.U71 no. 7999 622.06173

U.S. Dept. of the Int. Library.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25 D.C. - Price 25 cents

Generated on 2024-09-22 03:01 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google

Digitized by Google

Original from
THE OHIO STATE UNIVERSITY

CONTENTS

Page

Introduction and summary..... 1
Part I. - Research and technologic activities..... 2
Part II. - Publication abstracts..... 8
Explosives research and testing..... 8
1. Combustion and detonation in gases..... 8
2. The slow thermal decomposition of cellulose nitrate..... 9
3. Some salts of nitrocyanamide and their efficiency as primary explosives..... 10
Experimental coal mine and dust explosions research... 10
4. Some research problems of the development and control of coal dust explosions..... 10
5. Coal mine explosion research by the Bureau of Mines, 1954-1955..... 11
6. Explosion prevention by wet rock dusting and other measures near rapidly advancing coal faces..... 14
7. Effectiveness of wet rock dusting..... 14
8. Experiments on water infusion in the Experimental Coal Mine..... 16
9. Explosibility of American coals..... 16
10. Explosion and fire hazards of combustible dusts..... 17
11. Recent findings on dust explosions..... 17
12. Venting dust explosions..... 20
13. Radiative transfer in dust flames..... 21
Explosion, flame and combustion research..... 21
14. Flammability limits of hydrocarbons at high temperatures and pressures..... 21
15. Considerations involved in handling kerosine. 22
16. The flammability characteristics of the system H_2-NO-N_2O-Air..... 23
17. Photographic studies of turbulent flame structure..... 24
18. Turbulent burning velocities of natural gas-air flames with pipe-flow turbulence..... 26
19. Applications of the electronic probe to the study of turbulent flames..... 27
20. Evidence for the wrinkled continuous laminar wave concept of turbulent burning..... 27

Generated on 2024-09-22 03:05 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

CONTENTS (Con.)

Page

21. Flame propagation in cylindrical tubes near the quenching limit..... 28
22. Fundamental flashback, blowoff and yellow-tip limits of fuel gas-air mixtures..... 29
23. Yellow-tipping of bunsen burner flames and related exchangeability of fuels in gas utility systems..... 29
24. Spontaneous ignition temperature of fuel-nitric oxide mixtures..... 30

ILLUSTRATIONS

Fig.

1. Large (No. 1) explosives test gallery at Bruceton, Pa..... 2
2. Diagram of gallery No. 1 showing details of 105° elbow..... 3
3. Streak schlieren photograph of gaseous deflagration (37.3 percent CO, 60.8 percent O_2, 1.2 percent H_2, 0.7 percent H_2O plus inert gases)..... 8
4. Schematic composite of nonsteady-state gaseous deflagration corresponding to figure 3..... 9
5. Heaps of coal cuttings partly covered with limestone, being readied for an explosion experiment at the Experimental Coal Mine (Bruceton, Pa.)..... 12
6. Eroded heaps of coal cuttings after explosion experiment of figure 5..... 13
7. Wet rock dusting by application of limestone-water slurry in Experimental Coal Mine..... 13
8. Explosion of titanium dust (300 milligram) in lucite tube apparatus used in laboratory to evaluate explosibility of dusts and powders..... 18
9. Effect of moisture on flammability of mixtures of high-volatile, bituminous Pittsburgh coal dust and limestone dust..... 19
10. Flat laminar graphite dust flame (200 milligrams per liter) burning in oxygen..... 22
11. Schlieren optical system for studies of turbulent flames..... 24
12. Direct time exposure (left) and high-speed schlieren (right) photographs of turbulent stoichiometric natural-gas-air flame (Reynolds No.=10,000)..... 25

Generated on 2024-09-22 03:11 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

RESEARCH AND TECHNOLOGIC WORK ON EXPLOSIVES, EXPLOSIONS, AND FLAMES: FISCAL YEARS 1957 AND 1958[1/]

by

Ruth F. Brinkley[2/] and Robert W. Van Dolah[3/]

INTRODUCTION AND SUMMARY

This report is the 18th of a series of reports originally issued annually, and more recently bienially, to acquaint the public with the work of the Federal Bureau of Mines in explosives technology. Part I reviews briefly the overall activities during fiscal years 1957 and 1958.[4/] Part II presents in abstract form the publications prepared by the Bureau that appeared during the period.[5/]

1/ Work on manuscript completed June 1960.

2/ Technical assistant, Office of the chief, Division of Explosives Technology, Bureau of Mines, Pittsburgh, Pa.

3/ Physical science administrator, chief, Division of Explosives Technology, Bureau of Mines, Pittsburgh, Pa.

4/ This review does not include activities such as security-classified research and investigations of a confidential nature, which are reported only to those immediately concerned, and short-term programs of a very limited scope, the results of which will be included in future summary publications.

5/ Additional information concerning individual unrestricted investigations will be made available upon request.

Generated on 2024-09-22 03:04 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

PART I. - RESEARCH AND TECHNOLOGIC ACTIVITIES

The Bureau's activities for fiscal years 1957 and 1958 continued to reflect an increased awareness of the need for more basic information on factors that determine the safety of permissible explosives. An experimental study utilizing the Bruceton up-and-down method was initiated as an improved procedure for evaluating the relative incendivity of permissible explosives. This first step in a long-range program to classify permissible explosives in terms of their relative safety has been received with much interest by the explosives industry. Work was continued to improve the safety of permissible compositions by minor changes in chemical formulation. Following continued satisfactory results obtained by the experimental addition of small amounts of sodium chloride, 16 permissible brands were modified by such additions and submitted for schedule testing; all but one were approved.

The marked increase in the number of shots fired at the large (No. 1) test gallery in the course of the above programs gave rise to an acute noise

FIGURE 1. - Large (No. 1) Explosives Test Gallery at Bruceton, Pa. With 105° Elbow.

Generated on 2024-09-22 03:12 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

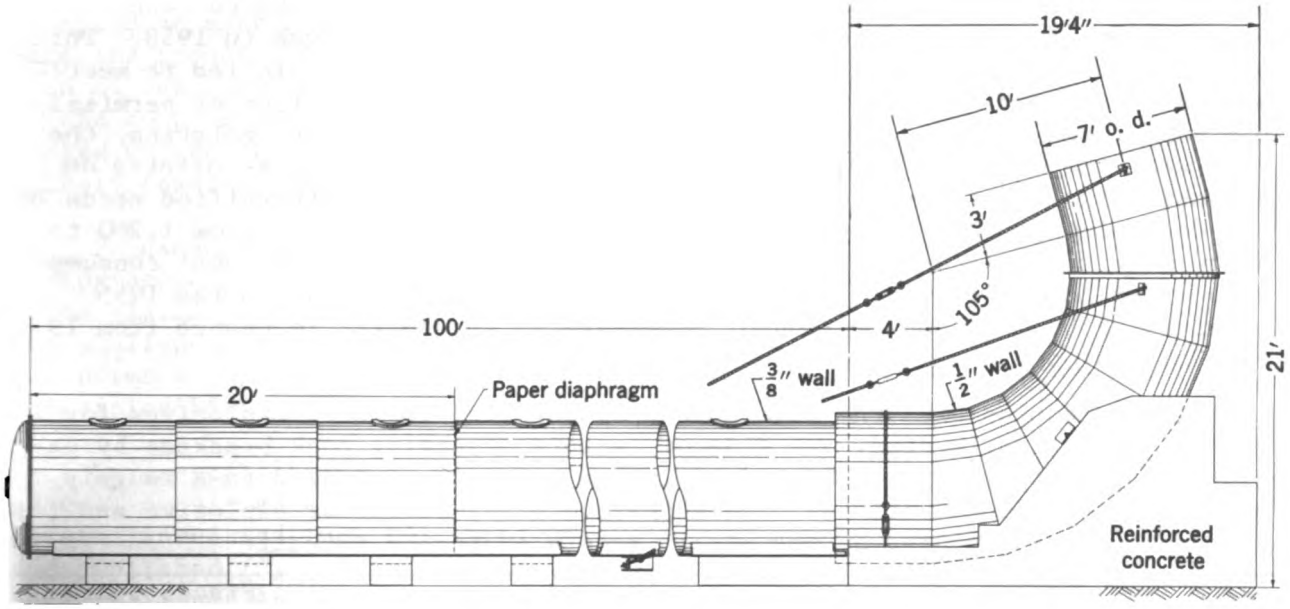

FIGURE 2. - Diagram of Gallery No. 1 Showing Details of 105° Elbow.

nuisance problem. Following an extensive series of sound-level measurements on a small-scale (1/6-scale) model of the No. 1 gallery, this problem was attenuated by addition to the test gallery of a 105° elbow that redirected the major blast effect upward (figs. 1, 2).

In research on the mechanism of firedamp ignition--one of the Bureau's major objectives--emphasis shifted temporarily to factors influencing the gallery test. One of these, the effect of free borehole space on the incendivity of explosives in the typical cannon shot, was the subject of an intensive investigation in a small gallery. Careful statistical analysis of the data showed a definite relation between ignition probability and the free borehole space under the experimental conditions. In conjunction with this study, an attempt was made to evaluate, quantitatively, the infrared radiation from the detonation products ejected from the borehole. An experimental program on the ignition of combustible gases by jets of hot gas was initiated to obtain information on the ignition of firedamp by explosives and on the flameproofing of mine equipment. Preliminary work with hydrocarbon-air mixtures showed that such mixtures had well-defined "hot-gas ignition temperatures" which bore little relation to the "spontaneous ignition temperatures".

During fiscal years 1957 and 1958, the Bureau performed 7,338 schedule and experimental tests of permissibles, other high explosives, and hazardous chemicals. The schedule for testing stemming devices (Schedule 27-A) was revised.6/ In connection with this revision, a study was made of the effect of several stemming materials on the volume of toxic gases produced by the

6/ Bureau of Mines Schedule 27-A, amendments as published in Federal Register, vol. 20, No. 54, March 18, 1955.

Generated on 2024-09-22 03:04 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

shot. Thirty-nine field samples were collected and checked.[7] The reduced number of field samples came as a direct result of the accelerated research program into factors influencing the safety of such explosives in 1958. Three blasting devices submitted for complete permissibility tests failed to meet safety requirements. As of December 31, 1957,[8] the active list of permissible explosives included 159 different brands; 19 of these were gelatins, the rest were the granular types. This wide variety of permissibles offered an extensive choice of physical characteristics that met the diversified needs of the coal mining industry, with rates of detonation that ranged from 1,200 to 5,600 meters per second (m./sec.)[9] In the United States, the total consumption of solid explosives rose in 1957 and then dropped almost to the 1955 level in 1958. The consumption of permissibles showed little change from 1956 to 1957, but declined sharply in 1958.[10]

In connection with the development of powerful low-cost explosives for open-pit blasting, a study was made of factors affecting rock breakage by explosives. Analysis of blasting data from a granite quarry led to a roughly quantitative relation between the detonation pressure of the explosive and its performance, as measured by the strain generated in the rock.[11]

7/

	Fiscal Year	
	1957	1958
Number of field samples collected	31	8
Met all tolerances	11	4
Failed gallery test	2	1
Failed to propagate	0	1

8/ Hanna, N. E., and Damon, G. H., Active List of Permissible Explosives and Blasting Devices Approved before December 31, 1957: Bureau of Mines Inf. Circ. 7832, 1958, 10 pp.

9/ These rates are now obtained using paper tubes, as is the practice in the explosives industry. For nongelatinous explosives, paper tube rates average about 83 percent of the steel tube rate.

10/ Industrial consumption of explosives, January-December 1956, 1957, 1958, in millions of pounds:*

	Coal mining			Total		
	1956	1957	1958	1956	1957	1958
Permissible explosives	103.7	103.5	80**	104.9	104.5	81**
Other high explosives) Blasting agents) Unprocessed ammonium nitrate)	172.7	245.7	***	898.5	912.6	***
Liquid oxygen	17.7	13.8	***	17.7	13.8	***
Black powder	2.9	2.4	1.8	5.6	3.7	2.5
Ratio of permissible to black powder consumption	35.7	43.1	44.4**			

* Based on Mineral Market Report No. MMS 2837, Mineral Industry Surveys, U. S. Dept. of the Interior, Bureau of Mines, and the monthly reports of the Institute of Makers of Explosives.

** Estimated.

*** Not available.

11/ Work performed in collaboration with the College Park, Maryland, Station and presented at the 2d Annual Symposium on Mining Research, Missouri School of Mines, Rollo, Missouri, November 1956; publication as a Rept. of Investigations is in progress.

Generated on 2024-09-22 03:03 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

The steadily increasing use of fuel oil-sensitized fertilizer-grade compositions based on ammonium nitrate for blasting in open-pit mines and quarries prompted an extensive study of field practices. Points of special interest were the trends toward charge initiation with heavy detonating fuse; elimination of inert coating usually found on the nitrate; and possible utilization of the compositions for underground mining. An experimental study was initiated on the sensitivity and potential hazards from toxic fumes of these relatively insensitive compositions.

Fundamental research on explosives and explosions continued with the photographic study of detonation waves in gaseous explosions and shock tubes (1).12/ Research on the slow thermal decomposition of cellulose nitrate was published during this period (2). In connection with the development of new primary explosives, a laboratory study was completed on the preparation and explosibility of heavy metal salts of nitrocyanamid (3).

Large-scale tests of hazards encountered in the underground exploitation of coal continued actively at the Experimental Coal Mine (Bruceton, Pa.). Several investigations initiated in the previous report period were completed and published (4). Problems considered included the underground storage of coal cuttings, in terms of Federal Public Law 552 (July 16, 1952) regarding the accumulation of dangerous quantities of combustibles in underground workings (5); various new methods of rock dusting made necessary by mechanized mining practices, in particular various techniques for the application of wet rock dust near rapidly advancing faces (5,6,7); water infusion of boreholes as a means of allaying coal dust (8); and hazards associated with loaded mine cars parked in entries (5).

Prompted by recent British research which aroused great interest in the use of high expansion foam for the remote control of fires that cannot be attacked by standard procedures, an investigation was initiated to study the applicability of this technique to American mining conditions (room-and-pillar extraction, multiple entries). Ignition hazards created by "cutoff" (accidentally exposed) charges of explosives were the subject of another new investigation. Transport and deposition of float dust by ventilating currents were studied in the entries of the Experimental Coal Mine. Light water troughs and rock-dust loaded shelves were used experimentally to supplement normal mechanical rock dusting near rapidly advancing faces. Various spray-applied liquid adhesives were tested as agents for binding coal dust to rib and roof surfaces. Laboratory experiments were initiated to study conditions conducive to gas ignition by frictional sparks from roof bolts. Three public demonstrations were conducted illustrating safe and hazardous mining practices.

Programs directed toward limiting and preventing industrial dust explosions continued in the laboratory and in the dust explosion galleries (9, 10). The inhibitive effect of moisture was observed for various ranks and particle sizes of coal dust; velocities of dust flames in ducts were measured by several independent methods; various screen devices were used experimentally for

---

12/ Numbers in parenthesis refer to papers in Part II.

581538 O - 61 - 2

Generated on 2024-09-22 03:12 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

quench-venting dust explosions; methods for controlling dust explosions in the initial slow stage were studied (11). The effect of various material and design factors on explosion venting was investigated (12). Explosion characteristics of 155 dust samples submitted by various industrial and governmental organizations were evaluated in the laboratory.13/

The role of radiation in heat transfer across laminar dust flames was studied by means of a rotating-film photographic technique (13). Work was begun to check experimental burning velocity data obtained for various dust flames against theoretical values; this involved measuring the burning times of individual particles.

In the Bureau's gas explosions work, research continued on new hazards introduced by the high temperatures and pressures that characterize many modern processes (14). Recurrent explosions and fires on oil tankers prompted investigations of hazards associated with loading kerosine (15) and the elimination of combustible vapors from shipboard storage areas. The study of flame and explosion characteristics of aircraft fuels and hydraulic fluids under flight conditions entered its seventh year. To obtain information on combustion in oxidants other than oxygen or air, flammability characteristics of hydrogen were measured in mixtures of nitric oxide, nitrous oxide and air (16). Explosion hazards associated with the operation of titanium-melting furnaces were the subject of a brief investigation. The stability of acetylene-ethylene mixtures at elevated temperatures and pressures was determined. Limits of flammability and spontaneous ignition temperatures were evaluated for 45 combustible gases and vapors by the now-classic Bureau of Mines procedure; quenching or inerting effects of water vapor, carbon dioxide, nitrogen, flue gas, and bromochloromethane were evaluated in a few systems. In connection with a nationwide program on the reproducibility of spontaneous ignition temperature values, sponsored by the American Society for Testing Materials, a series of measurements were made in the standard Bureau of Mines apparatus.

In the Bureau's long-standing fundamental research on the physics and chemistry of flames, effort was directed toward obtaining new information on turbulent flame structure. Turbulent flames were studied by schlieren, shadow, smoke, and direct photography, and the suitability of the different methods for these studies was evaluated (17). Turbulent burning velocities were measured as a function of flame height (18), by means of a radiation photometer and an electronic probe developed expressly for this type of work (19). These methods were applied also in an attempt to establish experimental evidence of the continuous laminar flame within the turbulent flame brush (20). Combustion products of turbulent flames were analyzed.

13/ Materials submitted included coal mine dusts, coke, factory and foundry dusts, stearates, fungicides, cotton seed meal, soy bean meal, gluton, flour, sugar, wheat starch, dyes, silicon carbide, aluminum-lithium alloy, titanium, metal sulfides and other metal compounds, detergents, acrylic polymer, polyethylene, epoxy resin, synthetic rubber, new plastics and related compounds, food supplements, drugs, etc.

Generated on 2024-09-22 03:09 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

Flame speeds of laminar flames were measured near the quenching limit (21). A comprehensive review was made of work performed by the Bureau for the gas industry since 1950 to provide basic information on the interchangeability of fuel gases and on gas burner design (22). New information was obtained on yellow tipping of burner flames (23). Primary combustion products of rich laminar flames and stoichiometric turbulent flames were analyzed with the mass spectrometer; the data will be used in a study of noxious gases liberated by domestic gas appliances and industrial gas furnaces. A literature survey was made of nearly 200 publications in the field of combustion and flames that appeared during 1956.14/

In research on gas ignition by static electricity, progress was made toward establishing a relation between the width of the spark gap and the quenching distance. A series of spontaneous ignition temperature measurements on fuel-nitric oxide mixtures furnished evidence on the chemical reactions of nitric oxide in flames (24), and prompted an electric-spark ignition study of these mixtures.

In addition to published research, the Bureau also participated in the national defense effort through a number of security-classified projects, under the direct sponsorship of the Armed Forces or in cooperation with industrial organizations engaged in defense work. Investigation of disastrous explosions and fires, and of potentially hazardous situations was continued as a service to civil and military authorities.

An earlier study of explosives production and utilization in the Far East was extended in February 1957 by G. H. Damon, in a tour that included Japan, Burma, India, and Pakistan.

The Bureau also took an active part in meetings of various American scientific and technical groups, and in international gatherings which included the Ninth International Conference of Directors of Safety in Mines Research (Heerlen, Netherlands and Brussels, Belgium, June-July 1956); the Sixth Symposium (International) on Combustion (New Haven, Connecticut, August 1956); and a meeting of Directors of mine safety research establishments at Verneuil and Paris, France (September 1957) where R. W. Van Dolah, represented the Bureau of Mines. Current research of the Bureau concerned with mine safety was presented at these meetings; contacts with other groups working in related fields were established and consolidated.

14/ Wolfhard, H. G., and Burgess, D. S., Combustion and Flames: Ann. Rev. Phys. Chem., vol. 8, 1957, pp. 389-412.

Generated on 2024-09-22 03:02 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

PART II. - PUBLICATION ABSTRACTS

Explosives Research and Testing

1. Greifer, B., Cooper, J. C., Gibson, F. C., and Mason, C. M., Combustion and Detonation in Gases: Jour. Appl. Phys. vol. 28, No. 3, 1957, pp. 289-294.

A photographic investigation of combustion in gases was made to observe experimentally the mechanism of initiation and structure of detonation waves. Schlieren photographs of hydrogen-oxygen and carbon monoxide-oxygen explosions were made in a rectangular shock tube, using precision optics and a rotating mirror camera (fig. 3).

FIGURE 3. - Streak Schlieren Photograph of Gaseous Deflagration (37.3 percent CO, 60.8 percent O_2, 1.2 percent H_2, 0.7 percent H_2O plus inert gases). Arrows Show Autoignitions in the Induction Zone Which Progressively Narrow Distance Between Combustion Zone and Shock Wave to Produce Steady-State Detonation.

The photographs show that compression waves generated during the early stages of propagation of the combustion soon steepen into a shock wave which travels ahead of the combustion wave (zone of chemical reaction). This combination of shock and combustion wave is characteristic of a nonsteady deflagration state in the moments before stable detonation is initiated (fig. 4). The distance between the two waves narrows as the reaction progresses down the tube due to the continued formation by autoignition of new combustion centers ahead of the combustion wave. Eventually the combustion wave overtakes the shock wave and supplies it directly with energy from the chemical reaction; at this moment stable detonation is initiated.

The internal structure of steady-state detonations was different from nonsteady-state deflagration; whereas the distance between the shock and the zone of chemical reaction was of the order of several centimeters in the

Generated on 2024-09-22 03:01 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

nonsteady-state deflagration, this distance in the steady-state detonation was too small to be resolved by the optical system (less than 1 mm.). Other structural features such as spinning detonation and a high-frequency oscillation of propagation velocity also were considered.

2. Gelernter, G., Browning, L. C., Harris, S. R., and Mason, C. M., The Slow Thermal Decomposition of Cellulose Nitrate: Jour. Phys. Chem. vol. 60, 1956, pp. 1260-1264.

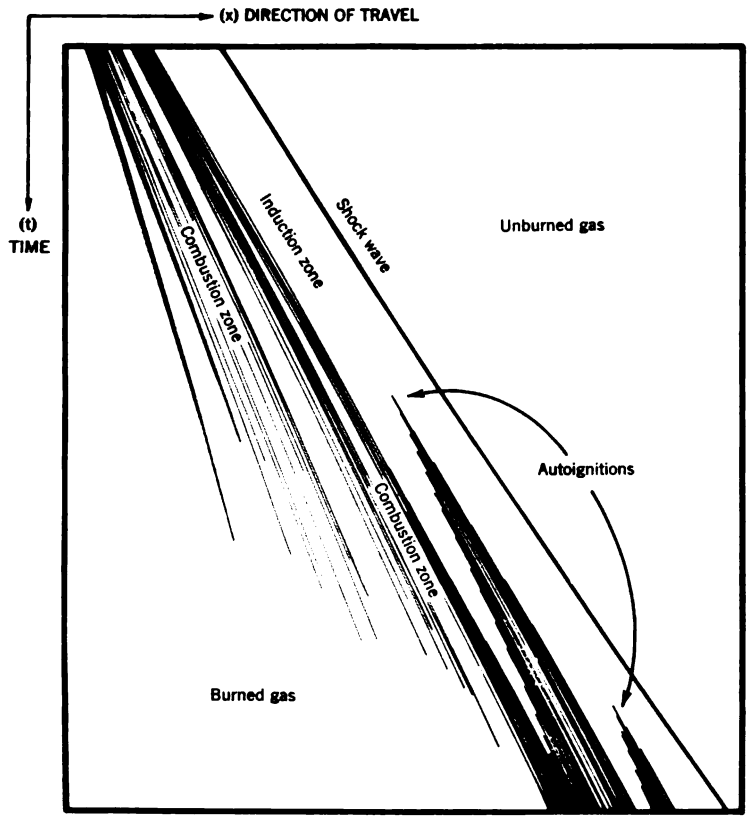

FIGURE 4. - Schematic Composite of Nonsteady-State Gaseous Deflagration Corresponding to Figure 3.

On the assumption that the decomposition of cellulose nitrate proceeds through one or more sequences of reactive intermediates, slow thermal decomposition was used to establish the principle sequence involved. The problem was approached in two ways: (a) Cellulose nitrate tagged with isotopic N^{15} on the sixth carbon atom of the glucoside unit was decomposed at low pressure; (b) highly nitrated cellulose nitrate was heated in a current of wet gas and a study was made of the gaseous decomposition products.

Decomposition of the tagged material showed that the nitrate groups in the second and third positions of the glucoside unit have a lower thermal stability. The following reaction sequence, postulating early cleavage between the second and third carbon atoms, was proposed:

$$\begin{array}{l} R\text{—}CHONO_2 \\ \quad\quad | \\ R'\text{—}CHONO_2 \end{array} \longrightarrow \begin{array}{l} R\text{—}CHO\cdot \\ \quad\quad | \\ R'\text{—}CHONO_2 \end{array} + NO_2$$

$$R\text{—}CHO\cdot \longrightarrow RCHO + R'\text{—}C\cdot HONO_2$$

$$\begin{array}{l} R\text{—}CHO\cdot \\ \quad\quad | \\ R'\text{—}CHONO_2 \end{array} \longrightarrow RCHO + R'\text{—}C\cdot HONO_2$$

$$R'\text{—}C\cdot HONO_2 \longrightarrow R'CHO + NO_2$$

Generated on 2024-09-22 03:00 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

3. Harris, S. R., Some Salts of Nitrocyanamide and Their Efficiency as Primary Explosives: Jour. Am. Chem. Soc. vol. 80, 1958, pp. 2302-2305.

Explosive properties of potassium nitrocyanamide reported by an earlier investigator (A. F. McKay, and others, Can. J. Research 28B, 683, 1950) prompted an investigation into the possibility of preparing the heavier metal salts of nitrocyanamide as potential primary explosives.

The salts were prepared either by metathetical reaction between silver nitrocyanamide and the metal chloride in solution, or by treating the solid metal carbonate with an acetonitrile solution of nitrocyanamide. The barium, cadmium, calcium, cobalt, copper (II), lead, lithium, silver sodium, strontium, tin (II) and zinc derivatives were prepared. Of these, only barium and silver nitrocyanamide appear to have any potential for use as primary explosives.

Experimental Coal Mine and Dust Explosions Research

4. Hartmann, I., Some Research Problems of the Development and Control of Coal Dust Explosions: Bull. Univ. of Missouri, Sch. of Mines, vol. 94, 1957, pp. 97-122.15/

A concise but comprehensive survey is made of the activities of the Bureau of Mines in this field since 1910. A brief history and description of the Experimental Coal Mine at Bruceton, Pa. is followed by a discussion of dust explosions in general and more especially of underground coal dust explosions. Various existing methods for preventing and reducing mine explosions are considered. Recent experimental investigations by the Bureau are described.16/

These include: Experiments on short-delay blasting of coal; ignition of coal dust by permissible explosives; laboratory explosibility study of American coals; hazards of underground storage of coal cuttings; effect of loaded mine cars on explosion propagation; effect of excessive accumulation of coal dust and fine coal in mine entries; effect of moisture on explosibility of coal dust; fire and explosion hazards in thermal coal drying plants; water infusion for suppressing coal dust formation; lessons from intensive dust sampling of a coal mine; rock dust requirements on floor and on rib-roof surfaces of mine; "blanket" rock dusting on floor of entries; promoting adherence of rock dust on mine surfaces; distribution of rock dust by permissible explosives; bag-type rock-dust devices for limiting explosion propagation; wet-rock dusting as an explosion prevention measure; water barriers and rock dust barriers; transport of dust by the air current.

15/ Hartmann, Irving, Studies on the Development and Control of Coal-Dust Explosions in Mines: Bureau of Mines Inf. Circ. 7785, April 1957, 27 pp.

16/ For further details see individual reports of these investigations, especially reference 5, 7, and 8 of the present circular.

Generated on 2024-09-22 03:09 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

5. Hartmann, I., Nagy, J., Rauschenberger, J. K., and Mitchell, D. W., Coal Mine Explosion Research by the Bureau of Mines, 1954-1955: Bureau of Mines Rept. of Investigations 5264, 1956, 26 pp.

Research conducted during 1954 and 1955 in the Experimental Mine is described briefly. These investigations relate chiefly to special problems created by mechanized mining practices:

Underground storage of coal cuttings. - The seams in most American bituminous coal mines are undercut, shearcut, or topcut before blasting. The cuttings are generally loaded out with the rest of the coal. However, in some mines this method is not economical and the cuttings are stored in random heaps or in layers on the floor of rooms and entries.

Following passage of Federal Public Law 552, which provides for the prohibition of an accumulation of dangerous quantities of coal and other combustible material in active underground workings, it became necessary to evaluate any potential hazard associated with the underground storage of coal dust. An experimental investigation established that although storage of coal cuttings in the face area where coal dust is normally present does not increase the severity of the explosion, the presence of the coal cuttings can enhance propagation of a coal dust explosion (figs. 5 and 6). Although rock dust alleviates this condition, the removal of combustible cuttings from the mine is recommended.

Thick "blanket" rock dusting on floor entries. - At many mines it has been the practice to apply a thick (blanket) rock-dust layer on the floor of entries and to neglect rock dusting of ribs and roof surfaces. As coal dust is dispersed more readily from the ribs and roof than rock dust is dispersed from the floor it is possible for a widespread explosion to develop under these conditions. This was clearly established by tests in the Experimental Mine which showed that rock dust on the floor alone, even in excessive quantities, could not compensate for a deficiency of rock dust on the ribs and roof.

Adherence of rock dust to rib and roof surfaces. - During normal application of rock dust with machines, difficulties often are experienced because of inadequate adherence of rock dust to the roof and rib surfaces, especially when they are dry and smooth. Because of the great importance of rock dust on ribs and roof, a limited study was made of methods for improving its adherence. The results suggest that it may be helpful to moisten the rib and roof surfaces shortly before, or simultaneous with, rock-dust application.

Wet rock dusting near rapidly advancing faces. - Public Law 552 provides that, with certain exceptions, all underground mines shall be rock dusted to within 40 feet of all faces. In mines using continuous mining machines a working face may advance several hundred feet in a day, necessitating rock dusting during the working shift. Generalized rock dusting with machines is a very dusty operation and one that is not suited for use near men and expensive machines. This means that long sections of entries are often left undusted, thus creating a serious hazard.

Generated on 2024-09-22 03:03 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

FIGURE 5. - Heaps of Coal Cuttings Partly Covered With Limestone, Being Readied for an Explosion Experiment at the Experimental Coal Mine (Bruceton, Pa.).

Various substitute methods were tried to correct this hazard. The most extensively investigated procedure was the application of wet rock dust either as a premixed slurry (fig. 7), or by mixing dry dust with water at the nozzle of the dusting machine. The results showed that protection against explosions near rapidly moving coal faces, could be achieved without undue difficulty by applying wetted rock dust to the ribs and roof. Light overhead cross shelves covered with rock dust, and light transverse water troughs were also effective. In all instances the coal dust on the floor must be neutralized by dry rock

Generated on 2024-09-22 03:01 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

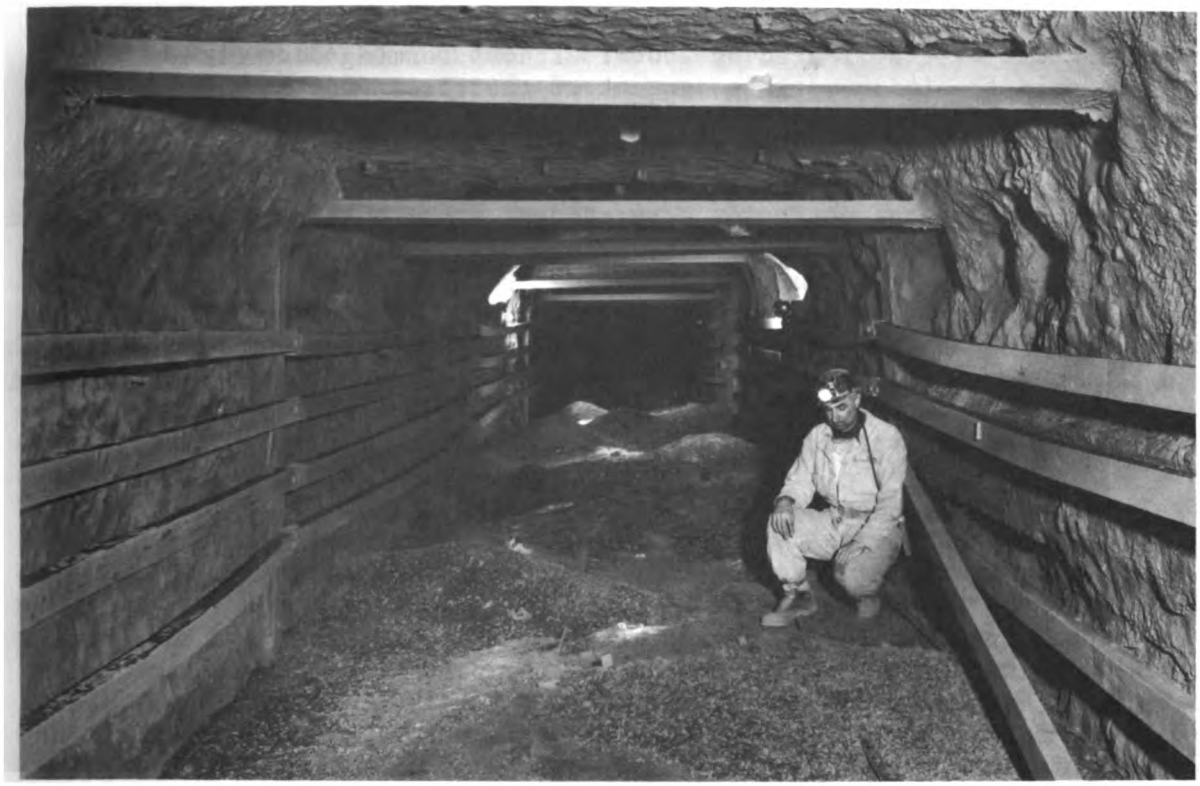

FIGURE 6. - Eroded Heaps of Coal Cuttings After Explosion Experiment of Figure 5.

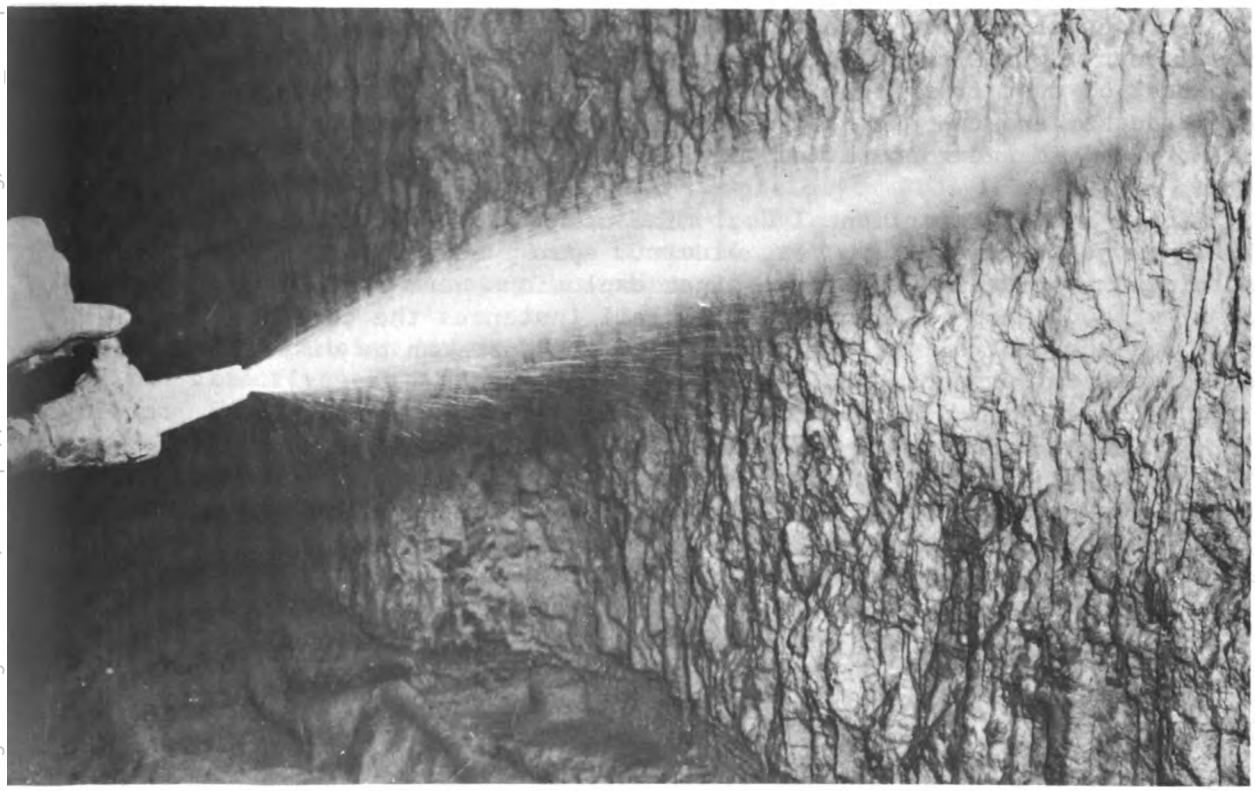

FIGURE 7. - Wet Rock Dusting by Application of Limestone-Water Slurry in Experimental Coal Mine.

581538 O - 61 - 3

Generated on 2024-09-22 03:09 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

dust which could be distributed by shovel without forming dust clouds. In no instance should the incombustible content of the floor dust be less than 65 percent.

Effect of loaded mine cars in entries on propagation of explosions. - In a recent mine explosion one factor suspected of contributing to the widespread propagation of flame was the presence of several trips of mine cars loaded on the previous day and left standing at various points in the entries. As loading cars and scheduling their haulage was standard practice it was important to determine the effects of loaded mine cars on mine explosions. Investigation showed that under certain conditions, mine cars filled with fine coal parked in the path of an explosion could greatly increase the length of flame travel, even in well-dusted entries.

6. Hartmann, I., and Nagy, J., Explosion Prevention by Wet Rock Dusting and other Measures near Rapidly Advancing Coal Faces: Proc., Coal Min. Inst. America, December 1955, pp. 102-111.

Modern mining techniques coupled with the increased use of electrically powered equipment, give a new importance to the prevention of mine explosions and especially to their control during the relatively slow incipient stage. Proper rock dusting has proved valuable for this purpose, however, experience has shown that to be effective rock dust must be applied to within a least 40 feet of all active coal faces, a requirement which may be difficult to meet at rapidly advancing faces.

Various alternative procedures that have been developed and tested in the Experimental Coal Mine are: Automatic dispersal of dust from suspended bags; dispersal of dust from light, movable shelves; dispersal of water from overhead troughs; and the use of a mixture of limestone dust and water applied as a slurry on rib and roof surfaces, either mechanically or by hand.

Tests at the Experimental Coal Mine using different ignition sources (blown-out shot of black powder, electric spark) showed that all the above techniques provided protection against explosions near rapidly moving coal faces, without undue difficulties. In all instances the coal dust on the floor must be neutralized with rock dust; the dust can be distributed with shovels without producing undesirable dust clouds.

To insure adequate re-dusting, the rate at which float coal dust is deposited should be observed and spalling should be checked regularly in entries protected by wet rock dust. In general, frequent application of small amounts of rock dust is recommended, as is a systematic effort against the formation and accumulation of large amounts of fine coal dust.

7. Hartmann, I., and Rauschenberger, J. K., Effectiveness of Wet Rock Dusting: Proc., 46th Ann. Convention, Mine Inspectors' Institute of America, Columbus, Ohio, June 1956, pp.110-117.

In the initial stages, the development of a coal dust explosion is relatively slow. As it propagates along the mine entry, effects of pressure and

Generated on 2024-09-22 03:00 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

radiant heat combine to increase its intensity. Therefore it is much easier to arrest an explosion near its source by starting application of inhibiting agents (rock dust) very close to the source.

For effective protection, rock dust should be distributed uniformly and continuously on all mine surfaces, in sufficient amount to make the incombustible content of the total dust at least 65 percent. In conventional mining, rock dust is distributed mechanically during off shifts, between working shifts, or on weekends. In modern highly mechanized mines where a working face may move several hundred feet daily, both the explosion hazard and the problems of rock dust distribution are greater. To maintain rock dust to within 40 feet of all active faces,17/ dust must be applied during the working shift creating dense dust clouds that reduce visibility, create a health hazard, and may damage expensive machinery.

In an attempt to remedy this situation, the Bureau of Mines has conducted an extensive investigation of the application of wet rock dust, a procedure based on the idea that after evaporation of the water, the dust will regain its dispersibility.

The investigation, carried out in the Experimental Mine, had two main objectives: (1) To determine whether wet rock dust can be applied during a working shift without becoming a nuisance and to find the relative amounts required for effective protection; (2) to study the effectiveness of wet rock dust in arresting large coal dust explosions.

The experiments showed that a premixed slurry of limestone and water applied with a gunite nozzle, or limestone and water mixed at the nozzle, can be used effectively and with little dust dispersion.

A minimum of four pounds of rock dust applied wet was needed per linear foot of entry to cover the ribs and roof completely. From 80 to 85 percent of the wetted dust adhered as compared with from 30 to 35 percent for dry dust. Surface-treated, moisture-resistant limestone proved to be more dispersible after drying than most ordinary limestones.

About 70 explosion trials were made in the main entry of the mine to study the effectiveness of wetted rock dust applied in various ways and proportions. These tests showed that dry limestone dust distributed by machine was more effective than wetted rock dust in arresting explosions; wetted dust was more effective after complete drying, than after partial drying; dry rock dust distributed on the floor in entries where wet dust had been applied to ribs and roof helped to limit flame propagation; explosions which were arrested readily when rock dusting was carried to within 50 feet of the face were difficult if not impossible to arrest when dusting started from 150 to 200 feet from the face.

17/ Federal Public Law 552 requires nearly all underground mines to be rock-dusted to within 40 feet of all faces.

Generated on 2024-09-22 03:08 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

Various sampling methods designed to evaluate the adequacy of rock dusting showed that the wetted dust was more adherent to mine surfaces but less dispersible and mixed less completely with coal dust. A number of points remain to be studied in connection with the use of wetted rock dust. Pending the results of these studies, the condition of wet-rock dusted surfaces should be checked carefully, especially for spalling.

8. Nagy, J., Hartmann, I., and Mitchell, D., Experiments on Water Infusion in the Experimental Coal Mine: Bureau of Mines Rept. of Investigations 5353, 1957, 12 pp.

The production of fine coal dust is an inherent part of nearly every phase of coal mining, especially of highly mechanized operations. Moreover, in coal seams that have been subjected to high pressures for a long period, and particularly in dry and friable seams, some very fine dust is present in the seam before mining. Much effort has been devoted to allaying and collecting at the source the fine coal dust released during mining. One of the comparatively recent techniques developed for this purpose is infusion of water into the coal seam. Generally the water is introduced through boreholes in the face before undercutting.

Experience in Australia, Belgium, France, Great Britain, and other foreign countries showed that in some instances water infusion can reduce the amount of airborne (float) coal dust as much as 80 percent. Infusion tests in a coal seam in pillars under great pressure at a Utah mine indicated that water infusion was effective in reducing dust.

In followup tests by the Bureau of Mines to evaluate the effectiveness of water infusion in the level, relatively shallow, bituminous Pittsburgh coal seam, thirteen experiments were performed, seven in infused coal and six in noninfused coal. The float dust dispersed into the ventilating air current during undercutting, drilling, shot firing, and loading was determined. The purpose of the investigation was to determine whether water infusion of the Pittsburgh-coal seam--characterized by pronounced, nearly vertical, face and butt cleats, which permit free flow of water from infusion holes directly to the face--would reduce the concentration of airborne dust during mining.

The data from these experiments showed that water infusion of the Pittsburgh coal seam did not reduce the amount of fine dust produced during mining operations as much as reported elsewhere. With and without infusion, the average dust concentration in the return air, 40 feet away from the working face, was 25 million particles per cubic foot during undercutting, 20 million during drilling, 75 million during shot firing, and 20 million during hand loading. The average concentration was 3 to 6 times higher at the working face. The concentrations were measured at an airflow of 1,600 cubic feet per minute at the face.

9. Hartmann, I., Explosibility of American Coals: Jour. of Am. Soc. of Safety Eng., vol. 1, No. 1, February 1956, pp. 9-12.

Pulverized coal is used extensively by modern industry in a wide variety of applications (pulverized-coal boilers, fluidized fuels, jet propulsion,

Generated on 2024-09-22 03:00 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

synthetic liquid fuels, plastics, etc.). In some applications the dust is normally suspended in a flammable atmosphere; in others it is normally dormant but may be dispersed accidentally. In either case an explosion hazard can exist.

To evaluate this hazard, the Bureau of Mines made a study of the explosive characteristics of several ranks of coal, ranging from lignite to meta-anthracite. This study was described in detail elsewhere.18/ The results showed that the explosibility of coal dusts generally increased with the volatile ratio, but not linearly; the hazard of a coal-dust explosion was several times greater in an oxygen atmosphere than in air; the explosibility increased inversely with the particle size; increases in the initial pressure and ambient temperature increased the explosion hazard; release of coal-dust explosions to adjacent confined areas could result in strong secondary explosions; primary and secondary coal dust explosions could be controlled effectively by the proper use of quenching agents.

10. Hartmann, I., Explosion and Fire Hazards of Combustible Dusts: Industrial Hygiene and Toxicology (Patty), vol. 1, ch. 16, sec. 2, 2nd revised ed. 1958, pp. 549-578.

The nature of dust explosion and fire hazards was reviewed. Physical and chemical factors affecting the explosibility of dusts were discussed. These included composition of the dust, its fineness, structure, and concentration; composition of the atmosphere; the ignition source; characteristics of the explosion space.

The results of recent laboratory studies on dust explosibility were presented. These include ignition temperatures; minimum explosive concentrations; minimum ignition energies; maximum pressures and rates of pressure rise associated with dust explosions; relative flammability. Fire hazard, as distinct from explosion hazard, was discussed.

Measures for preventing dust explosions and fires were given, supported by data for a number of important dusts.

11. Hartmann, I., Recent Findings on Dust Explosions: Chem. Eng. Prog., March 1958, pp. 107-111.

The Bureau's investigations of dust explosions fall into three categories:

(1) Laboratory evaluation of the explosive characteristics of combustible dusts and powders (fig. 8), and studies on various factors that affect explosibility, (2) basic research of the mechanism of ignition of dust particles

---

18/ Hartmann, I., Jacobson, M., and Williams, R. P., Laboratory Explosibility Study of American Coals: Bureau of Mines Rept. of Investigations 5052, April 1954, 8 pp.
Also Brinkley, R. F., and Van Dolah, R. W., Rept. of Research and Technologic Work on Explosives, Explosions, and Flames, Fiscal Years 1953 and 1954: Bureau of Mines Inf. Circ. 7804, 1957, pp. 86-98.

Generated on 2024-09-22 03:06 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

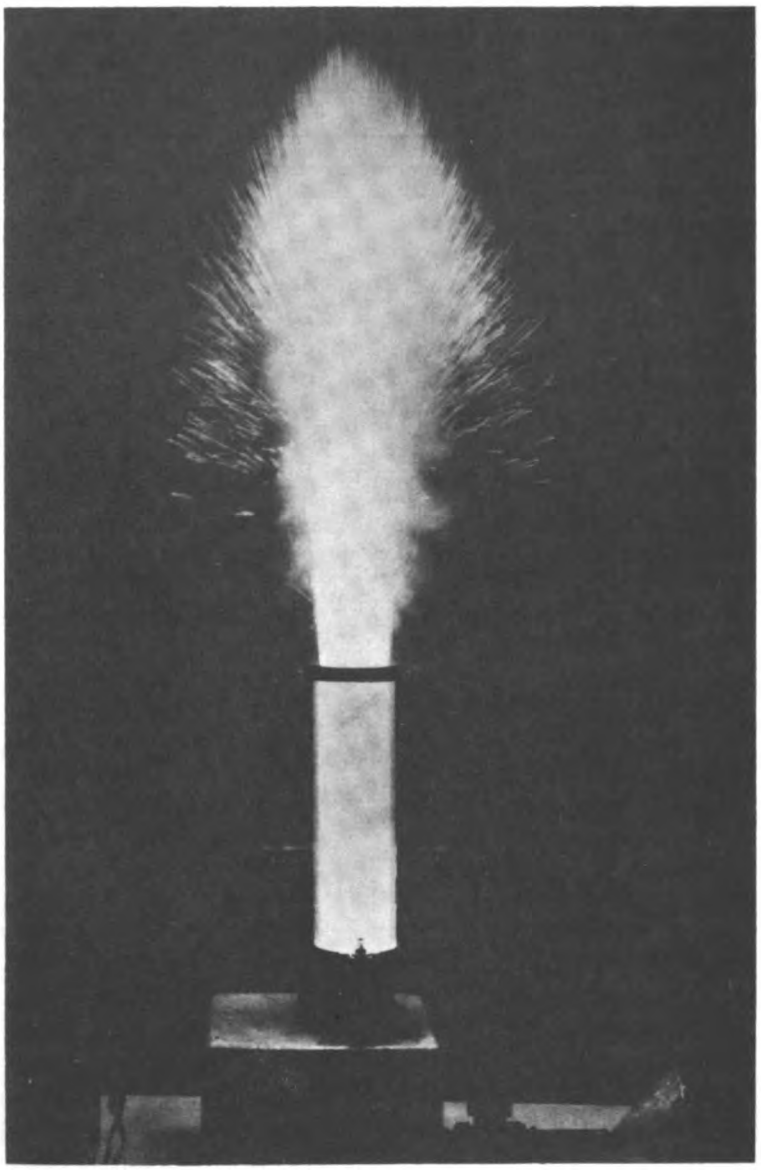

FIGURE 8. - Explosion of Titanium Dust (300 milligram) in Lucite Tube Apparatus Used in Laboratory to Evaluate Explosibility of Dusts and Powders.

and the propagation of combustion waves through dust clouds, (3) investigations in partly open chambers and galleries and in ducts on explosion venting, flame speeds, flame quenching, and related problems.

Recent studies include the following:

Effect of moisture on explosibility of dusts. - Moisture is known to have a palliative effect on the explosibility of many dusts. To evaluate the effect of moisture on the explosibility of coal dusts of various ranks and particle size, the amount of limestone dust required to prevent propagation of explosions of coal dusts with different moisture contents was determined in the laboratory. The tests showed (fig. 9) that a moisture content up to 5 percent had little effect on the relative flammability of the coals (Pittsburgh bituminous); further increase in the moisture content reduced flammability markedly. The effect of moisture was greater for coarse coal dust. The inhibitive effect of moisture was more than 3 times greater than that of powdered limestone.

Flame velocities in dust explosions. - Flame velocities of various dust explosions (cork, cornstarch, cellulose acetate, etc.) were measured in ducts of various lengths, cross section and geometry attached to a 1-cubic foot gallery. Measurements made by three independent methods (photoelectric cells, ionization probes and direct photography) were in agreement. Within the range investigated, the average flame velocity increased, though not linearly, with the duct length. The flame velocities within the duct increased almost linearly with the distance from the gallery toward the open end of the duct. The flame velocity increased directly with the dust concentration and inversely with the dust particle size. It decreased as the cross section of the duct

Generated on 2024-09-22 03:08 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

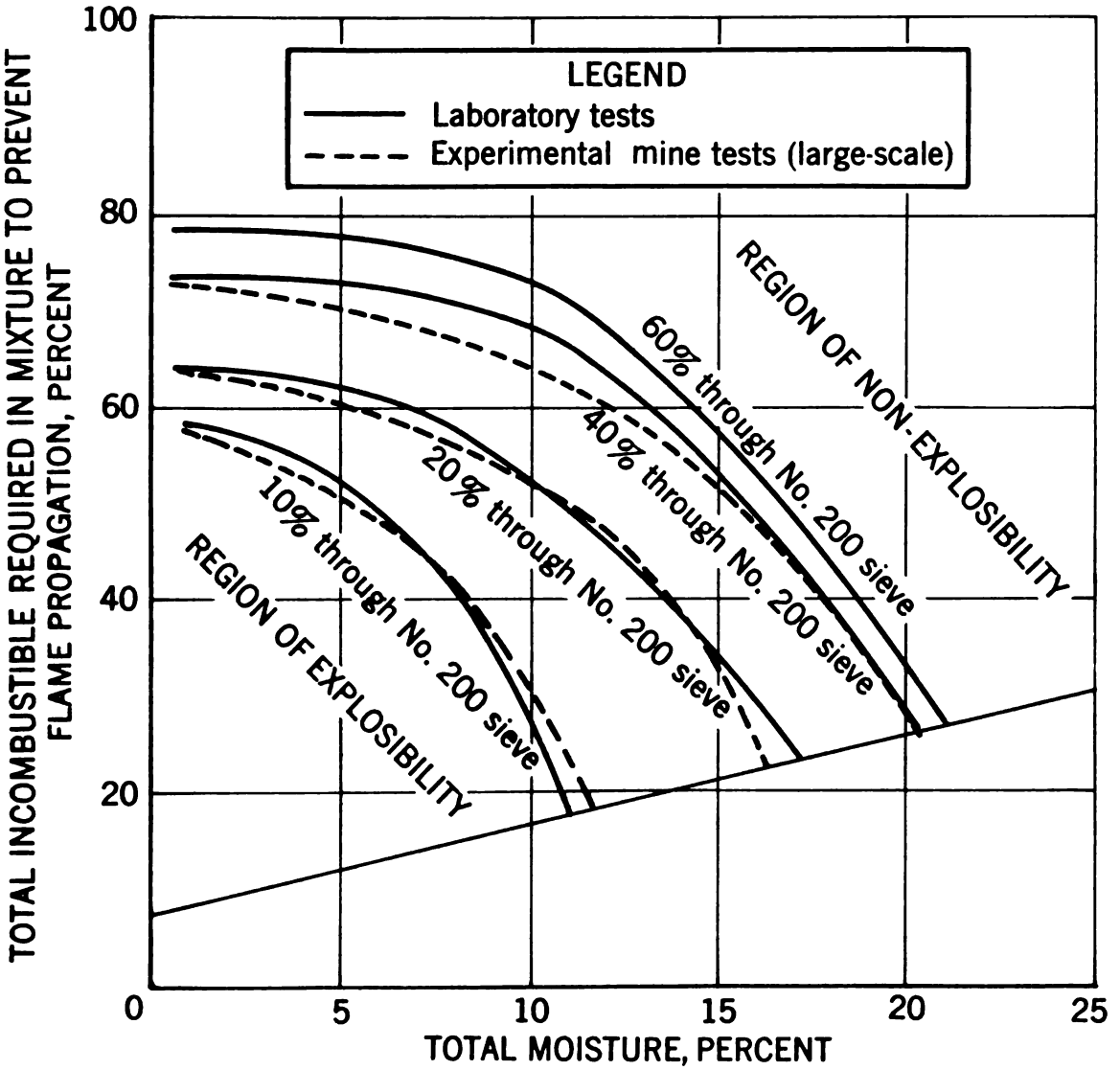

FIGURE 9. - Effect of Moisture on Flammability of Mixtures of High-Volatile, Bituminous Pittsburgh Coal Dust and Limestone Dust.

increased. The geometry of the cross section also had some effect on the flame velocity. The provision of a secondary vent at various locations along the duct reduced the flame velocity in inverse proportion to the distance of the vent from the gallery.

Explosion venting under special conditions. - The most effective vents are free or unrestricted openings, however, in practice it is frequently necessary to provide some type of closure. One recent development is the use of wire screens that simultaneously provide a means of releasing the explosion pressure and quenching flame. Gallery tests with various arrangements of single and multiple wire screens gives higher explosion pressures than tests with unrestricted vents. However, the screen devices promise to be effective in arresting flames of many industrial dust explosions within a short distance of their origin.

Generated on 2024-09-22 03:08 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

Quenching incipient explosions and preventing secondary ones. - It is highly advantageous to achieve control of a dust explosion in the initial, relatively slow stage. The problem of control in the incipient stage was studied in the 64- and 216-cubic feet galleries using various quenching agents dispersed from suspended containers such as polyethylene bags. In explosions of aluminum dusts, water alone was used. Water, limestone, and salt were used to combat coal dust explosions. The time between dispersion of the quenching agent and initiation of the explosion was found to be critical.

In many explosions, the initial ignition is limited to a relatively small amount of combustible in a small volume, however, the resulting disturbance can disperse dust off adjacent surfaces, thus providing fuel for subsequent explosions at more remote locations. In experimental studies, the arrangements used to prevent explosions from propagating from the 64-cubic feet gallery to the 216-cubic feet gallery were: (1) One or more vents in the duct between galleries; (2) dispersal of quenching agents (water, limestone, salt) from containers suspended in the duct; (3) dispersal of quenching agents from V-shaped troughs installed in the duct; (4) one or two water sprays installed in the duct.

12. Hartmann, I., and Nagy, J., Venting Dust Explosions: Ind. Eng. Chem., vol. 49, October 1957, pp. 1734-1740.

Adequate explosion vents in plants are highly effective in reducing structural damage from dust explosions occurring in enclosures, in that they promote rapid release of hot gases, flame, and dust. Unrestricted openings provide the most effective vents, however, as the use of such free vents generally is not practical, information is needed on the factors that determine the effectiveness of various venting devices.

In a recent investigation, venting requirements of dust explosions were studied in cubical galleries having volumes of 1, 64, and 216 cubic feet, with and without ducts attached to the vents. Parameters investigated include particle-size distribution of dust, concentration of dust clouds, and admixture of inert with combustible dust; manner of dispersing dust into a cloud; nature of igniting sources and their timing with formation of clouds; size, number, shape, and location of vents; length, shape, cross sectional area, and orientation of ducts; bends and diaphragms in ducts; presence of dust on the duct floor; secondary vents in ducts; and weatherhoods in ducts. Venting finite volumes to large adjoining chambers, prevention of secondary explosions, and simultaneous venting and flame quenching of dust explosions also were investigated.

Venting requirements were studied for explosions of fifteen inorganic and organic dusts, and pressure-vent ratio relationships were determined for relatively mild and strong explosions of several dusts. Of the dusts investigated, aluminum and magnesium powders were the most difficult to vent.

The nature of diaphragms, hinged panels, and other closures on vent openings proved highly important. The interposition of ducts between vents and the outside atmosphere greatly increased maximum pressures in some instances.

Generated on 2024-09-22 03:04 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

Secondary vents in such ducts increased their effectiveness, especially when located near the potential source of an explosion.

13. Cassel, H., Liebman, I., and Mock, W. K., Radiative Transfer in Dust Flames: Sixth Symposium (Internat.) on Combustion, Reinhold Publishing Corporation, New York, 1957, pp. 602-605.

Ordinarily radiation plays a minor part in the heat transfer across the combustion zone of explosive gas mixtures. However, it was suspected that its effect might be appreciable in dust flames. In the course of research on laminar aluminum dust flames, evidence of such an effect was first sought by comparing burning velocities of stationary Bunsen-type flames burning in air on burner tubes of different diameters. Burning velocities were evaluated from flame photographs by the truncated cone method. Contrary to expectation, the burning velocities on the small burner exceeded those on the large burner by approximately 15 percent for the coarse dust and 23 percent for the fine dust. As this result was believed due to curvature effects overshadowing radiative transfer the investigation was extended to flat laminar dust flames (fig. 10). These flames were self-sustaining when stabilized by an enveloping divergent gas stream. Minus 5-μ pulverized aluminum and graphite dusts were prepared (maximum sedimentation velocity, 0.2 centimeter per second). Fuel concentrations in the dispersions were determined from the volume, by flow rate and time measurement, and from the weight of filtered dust aspirated at the burner port. Burning velocities were determined by: (a) Measuring the ratio of volume flow into a central stream tube and its cross section at a level of the burning zone where stream lines were parallel, as derived from particle streak photographs on the basis of total flow measurement; flame diameters were determined from the same photographs. (b) From the velocity minimum in the unburned zone of central stream tube particles as micrographed on rotating film; flame diameters were determined from enlarged natural-size photographs. Within the range of flame areas studied, the average radiative contribution in heat transfer amounts to about 60 percent for graphite dust flames burning in oxygen and to about 35 percent for aluminum flames burning in air. The greater effect in graphite flames is in line with the greater absorptivity of this fuel.

Explosion, Flame and Combustion Research

14. Kennedy, R. E., Scott, G. S., and Zabetakis, M. G., Flammability Limits of Hydrocarbons at High Temperatures and Pressures: Chem. Eng. Prog., vol. 13, No. 3, March 1957, pp. 125M-126M.

The high temperatures and pressures which characterize many contemporary processes have introduced hazards not encountered at lower temperatures and pressures. Gas mixtures ordinarily considered as nonflammable become explosive, gas-phase reactions become violent, and normally stable gas mixtures undergo spontaneous reactions. As the effects of temperature and pressure on the flammability of a combustible cannot be calculated, they must be determined experimentally. For this purpose, special apparatus has been developed at the Bureau of Mines which can measure flammability characteristics (limits

Generated on 2024-09-22 03:02 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

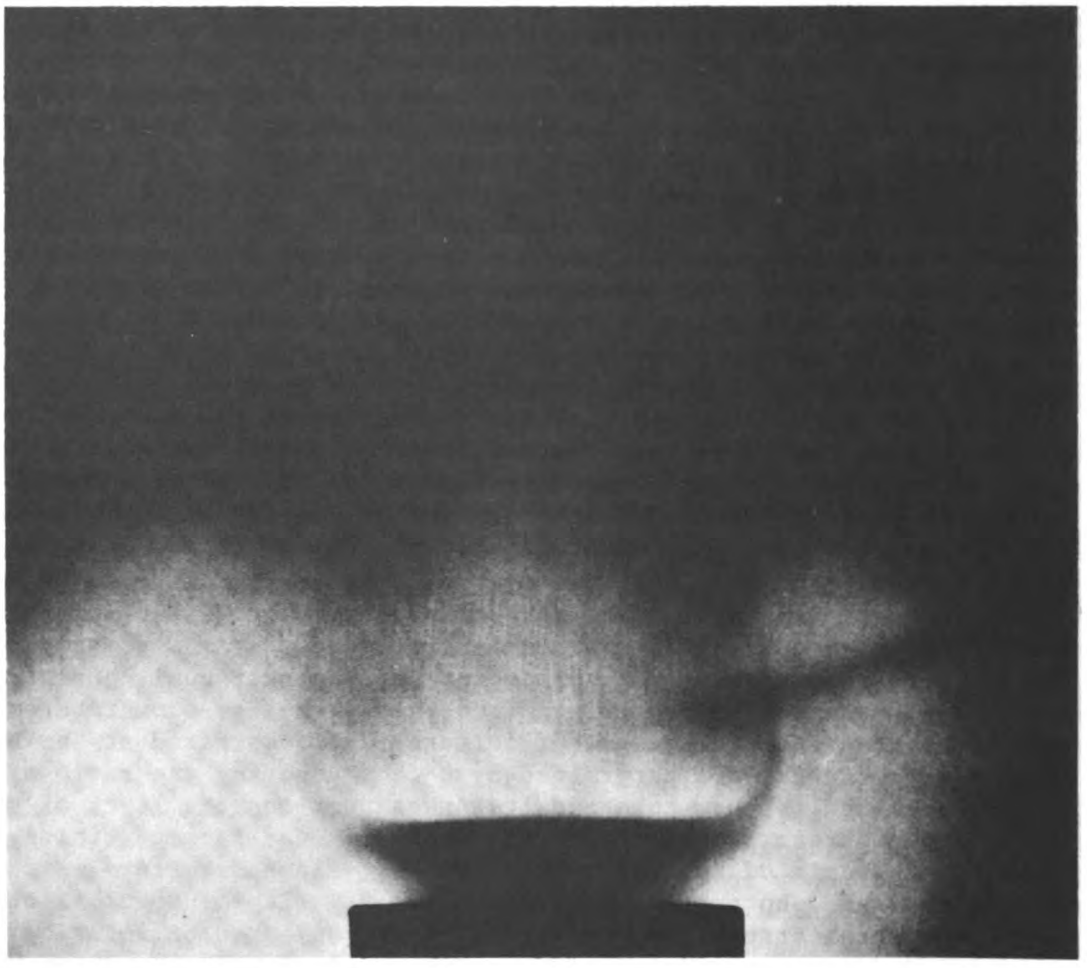

FIGURE 10. - Flat Laminar Graphite Dust Flame (200 milligrams per liter) Burning in Oxygen.

of flammability, spontaneous ignition temperature) at initial pressures above 10,000 pounds per square inch (lb./sq. in.).

Studies with these apparatus have shown that the limits of flammability of most combustible-oxidant systems become wider as the temperature or pressure increases. Thus data obtained at ordinary temperatures and pressures cannot be used to assess hazards associated with high temperatures and pressures. Similarly, an increase in pressure may decrease the spontaneous ignition temperature, thus making the use of high temperatures for a high-pressure process hazardous. Finally, in systems operating above 100 lb./sq. in., vapors from combustible fluids may ignite in air when projected against a surface heated to temperatures below the minimum spontaneous ignition temperature.

15. Zabetakis, M. G., and Rosen, B. H., Considerations Involved in Handling Kerosine: Proc., Am. Petrol. Inst., Sec. 3, Refining, vol. 37, 1957, pp. 296-301.

Kerosine forms explosive vapor-air mixtures when in contact with air at temperatures above its flashpoint. It can also form explosive vapor-mist air

Generated on 2024-09-22 03:01 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

mixtures and explosive foams in air at temperatures well below its flashpoint. These hazardous conditions can be eliminated most effectively by the addition of a sufficient quantity of inert gas to prevent flame propagation through the resultant mixtures.

The quantities of carbon dioxide, flue gas, or nitrogen required for this purpose were determined in cooperation with the Cities Service Research and Development Co. These values were used to obtain the minimum concentrations of oxygen for flame propagation at 300° F. as follows:

Inert Gas	Minimum O_2 requirement (Volume, percent)
Carbon dioxide.....	13.0
Flue gas.....	10.9
Nitrogen.....	9.9

The above values should be increased about 0.5 percent by volume for fine mist-vapor-air mixtures below 100° F. They can be increased still further for flame propagation through kerosine foam (17.8 percent O_2 for a fine kerosine foam in a CO_2-air mixture).

Experiments also were conducted aboard a type T-2 tanker during a kerosine-loading operation, to determine the effectiveness of a carbon dioxide blanket in reducing the oxygen concentration above the liquid to a safe level. Additional large-scale laboratory tests were planned to study the use of inert gas for preventing gas explosions during kerosine-loading operations.

16. Scott, F. E., Van Dolah, R. W., and Zabetakis, M. G., The Flammability Characteristics of the System H_2-NO-N_2O-Air: Sixth Symp. (Internat.) on Combustion, Reinhold Publishing Corp., New York, 1957, pp. 540-545.

To obtain information on combustible-oxidant systems using oxidants other than air or oxygen, an experimental study was made of the flammability of hydrogen in mixtures of nitric oxide, nitrous oxide, and air. Limits of flammability were determined at one atmosphere and room temperature in the standard Bureau of Mines apparatus. Some of the resulting limit curves obey Le Chatelier's law for limit mixtures; others show a marked deviation. The points of maximum deviation on the upper and lower limit curves occurred in the H_2-NO-air mixtures in which maximum quantities of NO_2 formed in the precombustion reaction. As these points were approached along the limit-of-flammability curves, the flame color went from white to orange. Measured flame speeds of the limit mixtures ranged from 24 to 100 centimeters per second (cm./sec.).

Generated on 2024-09-22 03:05 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

17. Grumer, J., Singer, J. M., Richmond, J. K., and Oxendine, J. R., Photographic Studies of Turbulent Flame Structure: Ind. Eng. Chem., vol. 49, February 1957, pp. 305-312.19/

To test various concepts of turbulent burning, particularly the concept of turbulent burning via flamelets, new photographic studies of turbulent flame structure were undertaken. As the main evidence in support of the fluctuating laminar wave consisted of very short duration schlieren, shadow, (a few microseconds) and smoke photographs of the turbulent flame brush, the first step was a comparative study to determine the reliability of these methods. Because of the similarity of schlieren and shadow photography it was possible to evaluate both these techniques by testing the schlieren method (fig. 11). The object-image ratio was 2. The light source was flashed for

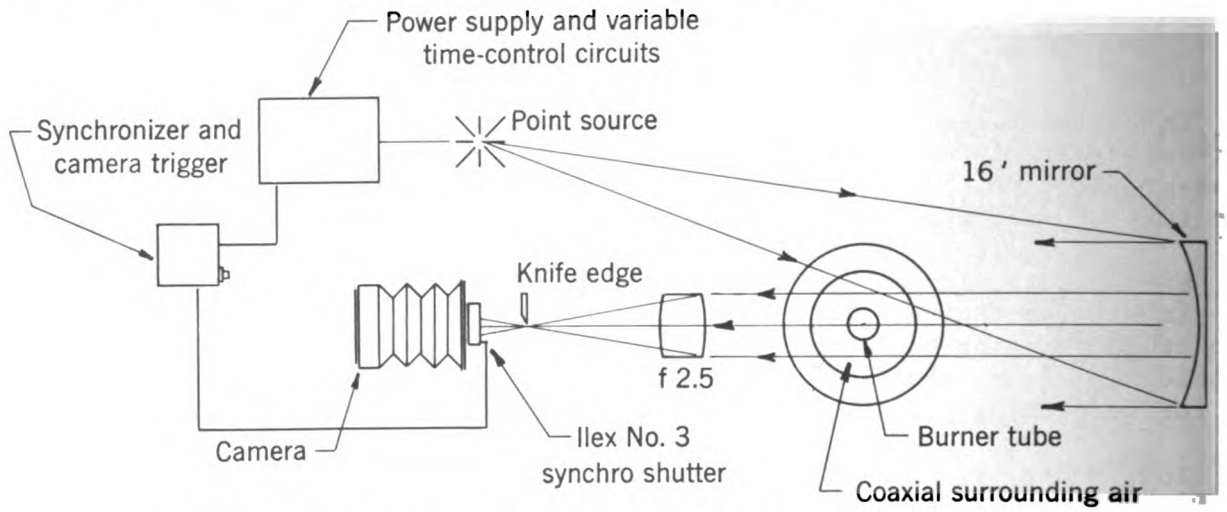

FIGURE 11. - Schlieren Optical System for Studies of Turbulent Flames.

times varying from about 10 microseconds to 2 milliseconds. The duration of each flash was measured with an oscilloscope. An analysis of a number of photographs obtained with this setup suggested that the schlieren was the result of density gradients that were composites of the interaction of the approach flow with heat from the flame holder and from the turbulent flame brush (fig. 12). The shape and position of these density gradients does not necessarily conform to the shape and position of the instantaneous turbulent flame. Hence, the schlieren photography, as used previously, is not a reliable method for analyzing the structure of the turbulent flame brush.

Photographs were also taken of turbulent flames containing ammonium chloride and zinc oxide smoke. The results indicated that the technique of smoke photography is not sufficiently clear-cut to be an accurate tool in resolving the structure of the turbulent flame brush.

19/ Portions of this material were presented at the meeting on "Combustion in Turbulent Flow," Applied Physics Laboratory, Silver Spring, Md., April 14-15, 1955 and Summarized in Grumer, J., Schlieren and Direct Photographic Studies of the Turbulent Flame Structure; Jet Propulsion, vol. 26, 1956, pp. 481-482.

Generated on 2024-09-22 03:04 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

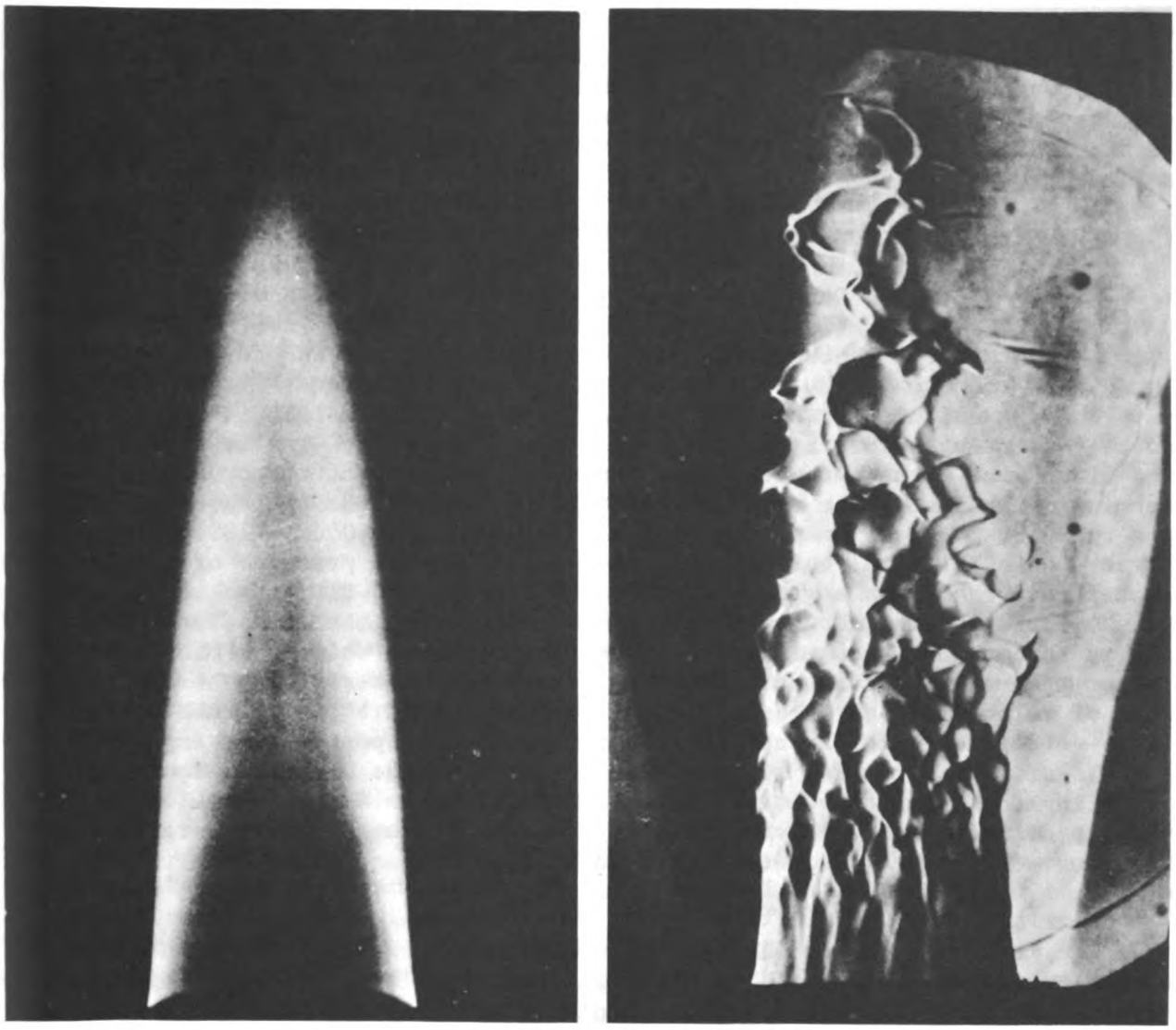

FIGURE 12. - Direct Time Exposure (left) and High-Speed Schlieren (right) Photographs of Turbulent Stoichiometric Natural-Gas-Air Flame (Reynolds No.=10,000).

The luminosity of the turbulent flame was photographed directly using orthochromatic and panchromatic film to provide more convincing evidence of the turbulent flame structure. Sufficient sensitivity was obtained by using an f:2 lens with a focal plane shutter speed of 0.002 second. The shutter moved at right angles to the axis of flow and the object-image ratio was approximately 10. Photographs were also taken with an f:1 lens and 0.001 as well as 0.002 second focal plane shutter speed. These photographs indicated that the turbulent flame brush was made of streaks of luminosity of various intensities suggesting flamelets. Many of these flamelets were inclined nearly parallel to the direction of flow. Careful analysis of the method used led to the conclusion that the structure shown by these direct photographs of the turbulent flame brush was not due to lack of photographic sensitivity or

Generated on 2024-09-22 03:11 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

shutter-produced distortions. Although these experiments were not sufficient to establish the structure of all turbulent flames, particularly of flames of high turbulence where a high concentration of flames would be indistinguishable from a homogeneous reaction zone, they were significant in that they did not suggest that the turbulent flame was made up of a laminar wave fluctuating with turbulence intensity or that the turbulent flame brush was a continuous reaction zone.

18. Richmond, J. K., Singer, J. M., Cook, E. B., Oxendine, J. R., Grumer, J., and Burgess, D. S., Turbulent Burning Velocities of Natural Gas-Air Flames with Pipe-Flow Turbulence: Sixth Symposium (Internat.) on Combustion, Reinhold Publishing Corp., New York, 1957, pp. 303-311.

Burning velocities were measured as a function of height in Bunsen flames to test existing theories of turbulent burning velocity. The mean position of the flame within the turbulent brush and the thickness of the brush were determined with a new type of flame radiation photometer developed especially for this work. Measurement for approach flows from 10,000 to 100,000 Reynolds number, on a 1-1/4 in. burner tube, showed that in the presence of the turbulent flame, there was a greater divergence of approach flow than would exist in the corresponding flow without a flame. Moreover, the flow divergence was always accompanied by an increase in static pressures which was many times larger than that corresponding to the laminar flame pressure. The distribution of velocities in the unburned gas was determined by pitot tube mapping. These velocities were extrapolated to the mean flame position by empirical functions. The direction of flow divergence along the flame was found by integrating the velocity values in the radial direction. Burning velocity values, defined as the velocity of the flame at its mean position relative to the flow of unburned gas, were computed by both the angle and the frustum method.

The intensity of turbulence in the approach flow was known from hot-wire anemometer measurements.[20/] To determine the turbulence intensity of the flame, the high level of ionization produced by the flame was used as a tracer of the turbulent fluctuations in the flame. This ionization was detected by the electronic probe developed at the Bureau of Mines (reference 19). Throughout the range of the probe (Re= 35,000 to 100,000), the probe measurements of turbulence were in agreement with hot-wire measurements in cold flow which indicated that flame-generated turbulence, if any, was small.

The experimental results obtained under these conditions gave no evidence of an increase in the burning velocity with height in open Bunsen flames, nor of the presence of flame-generated turbulence, for Reynolds numbers from 50,000 to 100,000.

20/ Little, B. H., Jr., and Wilbur, S. W.: NACA Tech. Note 2361 (1951).

Generated on 2024-09-22 03:04 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

19. Denniston, D. W., Jr., Oxendine, J. R., Knapschaefer, D. H., Burgess, D. S., and Karlovitz, B., Applications of the Electronic Probe to the Study of Turbulent Flames: Jour. App. Physics, vol. 28, No. 1, January 1957, pp. 70-75.

During a study of turbulent flames by the Bureau of Mines, it was necessary to measure the statistical distribution and the random fluctuating motion of the instantaneous flame front within the turbulent flame brush. This was accomplished by developing a negatively biased bare wire probe with suitable amplification and pulse height discrimination.

The probe was used for the three measurements bearing on turbulent flames; location of the most probable position of the combustion wave within the flame brush which determined a reference surface for calculating burning velocities; determination of the root mean square (r.m.s.) displacement of the wave from its most probable position, a quantity which plays an important part in theories of burning velocity; detection of "holes" or instantaneous discontinuities in the flame's ionization sheath which is an indication of flame instability.

In spite of limitations, the electronic probe proved useful in studies of the propagation, structure, and stability of turbulent flames. Where probe data was compared with data obtained by other techniques, agreement was satisfactory. In some areas of study the probe gave quantitative information not otherwise obtainable by existing methods.

20. Richmond, J. K., Donaldson, W. F., Burgess, D. S., and Grumer, J., Evidence for the Wrinkled Continuous Laminar Wave Concept of Turbulent Burning: Jet Propulsion, June 1958, pp. 393-399.

Understanding turbulent flame propagation required a flame model that represented the actual combustion processes over a useful range of conditions. The only model that found wide acceptance for laboratory burner flames was the wrinkled laminar flame structure. As there was much speculation concerning the range of applicability of this model, an attempt was made to obtain experimental evidence for the existence of a continuous laminar flame within the turbulent flame brush and it was suggested that this structure was applicable to much more highly turbulent flames than had been supposed.

Long vertical cylindrical burners were used and the flame was stabilized by an annular pilot flame. Pipe-flow and grid-induced turbulence were used. The flow conditions ranged from laminar flow at Re= 4,000 to turbulent flow at Re= 5,000 on a 9/16-in. burner tube; Re= 10,000 to Re= 100,000 on a 1-1/4 in. tube; and Re= 10,000 to Re= 160,000 on a 2-inch tube. The average approach velocity ranged from 14 to 155 feet per second (f.p.s.), with root mean square (r.m.s.) turbulent fluctuation velocities from 0 to 9 f.p.s. Estimated values of scale of turbulence varied from about 0.06 to about 0.20 in.

Measurements were made by the radiation photometer (see reference 18), the electronic probe, and smoke photography with NH_4Cl smoke (dissociation temperature ~ 325° C.) and ZnO smoke (sublimes at ~ 1,300° C.). The resulting

Generated on 2024-09-22 03:05 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

data were combined to show that a turbulent flame might contain a wrinkled continuous laminar combustion wave. Of all the evidence consistent with the wrinkled laminar flame model of turbulent flame structure, the photometer oscillograms seemed most nearly to fit the requirement for a crucial experiment to distinguish between the various models proposed. These oscillograms showed a correlation between the light from a steady laminar flame and the minimum light transients from a turbulent flame which strongly suggested that the wrinkled laminar flame model was pertinent over the entire range of conditions extending to pipe flows up to 150 f.p.s. through a 2-inch diameter tube and turbulence intensities up to 6 percent.

21. Singer, J. M., and von Elbe, G., Flame Propagation in Cylindrical Tubes near the Quenching Limit: Sixth Symposium (Internat.) on Combustion, Reinhold Publishing Corporation, New York, 1957, pp. 127-129.

An apparatus was developed for measuring flame speeds of downward propagation in tubes of near flame-quenching diameter and closed at the far end. Lewis and von Elbe[21] suggest that stream tubes passing through a moving combustion wave in narrow channels remain essentially unexpanded due to the large radial temperature gradient in the burned gas; as there exists no appreciable radial flow, the partly quenched wave travels along the tube at a flame speed approximately equal to the standard burning velocity. To test this theory, linear flame speeds were determined experimentally for methane-air flames propagating in tubes of diameter very close to the quenching dimension (within 1 millimeter). Where the flame traversed more than one-fourth of the tube length, the flame speed was approximately equal to the standard burning velocity. When the flame traversed less than one-fourth the tube length before extinction, the flame speed was less than the standard burning velocity and vibratory motion of the flame was generally observed. Linear flame speeds and dead space widths were also measured in tubes larger than the quenching distance (about 2-3 mm. greater) and used to calculate burning velocities, treating the flame as a hemisphere of diameter equal to that of the tube minus twice the dead space. The resulting burning velocities were very close to the standard values.

It follows that the burning velocity was not strongly depressed by the proximity of walls, even in channels approaching quenching dimensions, although the flame speed was strongly affected by channel size.[22] The observed dead space (for methane-air mixtures) was compared with the interspace between luminous and schlieren traces of conical laminar flames in free air. The dead space near quenching in these experiments was roughly equivalent to the separation of luminous and schlieren images of conical flames at stoichiometric compositions but becomes much larger for lean and rich mixtures.

21/ Lewis, B., and von Elbe, G., "Combustion, Flames and Explosions of Gases:" Academic Press, New York, 1951, p. 326.

22/ Singer, J. M., Grumer, J., and Cook, E. B., Significance of Quenching by Ports in Burning-Velocity Measurements by Bunsen Burner Methods: Jet Propulsion, November 1956, p. 989.

Generated on 2024-09-22 03:00 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

22. Grumer, J., Harris, M. E., and Rowe, V. R., Fundamental Flashback, Blowoff and Yellow-Tip Limits of Fuel Gas-Air Mixtures: Bureau of Mines Rept. of Investigations 5225, 1956, 199 pp.

Since 1950 the Bureau of Mines has been engaged in research aimed at providing basic information on the combustion characteristics of fuel gases and the principles of gas-burner performance. Most of the information thus obtained has appeared in journal articles and special publications of the American Gas Association. However, it seemed desirable to assemble the essential results of the program in a comprehensive report.

This report covers: Fundamental flashback and blowoff characteristics for a large number of fuel-gas mixtures. These are critical boundary velocity gradients for flames in free air, on burners with ports at room temperature and pressure. Burner aeration is characterized by the fraction of stoichiometric. The procedure for deriving corresponding values of port loading and percent primary air is given.

Fundamental yellow-tipping characteristics of fuel gases and yellow-tipping data for burners in free air with ports at room temperature and pressure. A graphical method is presented for correlating yellow-tipping over the range of practical port diameters.

The influence of port shape, depth, and temperature on flashback, blowoff, and yellow-tipping.

23. Grumer, J., Harris, M. E., and Rowe, V. R., Yellow-Tipping of Bunsen Burner Flames and Related Exchangeability of Fuels in Gas Utility Systems: Ind. Eng. Chem., vol. 48, 1956, pp. 2052-2061.

Yellow-tipping is not as serious a limitation in gas burner operation as flashback and blowoff. One can heat with a burner operating with yellow flames, and such flames often are desirable for radiant heating purposes. Where yellow-tip flames are undesirable it is usually because they deposit carbonaceous material on surfaces above the burner. Under some conditions they give off irritating aldehydes or excessive amounts of carbon monoxide. In designing burners or exchanging gases on existing burners, if yellow flames are to be avoided, it is important to understand the fundamental nature of the yellow-tipping phenomena.

Yellow-tip limits representative of most fuels have been measured. For each fuel there is a minimum characteristic fuel-air ratio that produces yellow in its flame. When secondary air diffuses into the flame the fuel-air ratio is leaner in the flame than in the burner and the apparent yellow-tip limits become richer.

Constant yellow-tip limits have been obtained as the limiting value for increasing port diameter and flow. These are the foundation of a graphical method of correlating yellow-tipping over a range of practical port diameters.

Generated on 2024-09-22 03:01 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY

A method for predicting the probable occurrence of yellow-tipped flames when fuel gases are exchanged in a gas distribution system has been combined with previous methodology for estimating the exchangeability of fuel gases. The agreement between prediction and experience of the gas utilities is good.

24. Wolfhard, H. G., and Strasser, A., Spontaneous Ignition Temperature of Fuel-Nitric Oxide Mixtures: Jour. Chem. Phys., vol. 28, No. 1, 1958, pp. 172-173.

It has been postulated that nitric oxide reacts in two ways in flames. In mixtures with fuels such as hydrogen or carbon monoxide, thermal decomposition of the oxide to oxygen and nitrogen is assumed to precede the oxidation reaction, giving very slow flames with large quenching diameters. When mixed with ammonia, nitric oxide gives relatively high burning velocities and small quenching diameters. This is attributed to a reaction of the oxide with the decomposition products of ammonia. The behavior of NO with hydrocarbons is intermediate, suggesting reactions with C_2CH and other radicals.

If this general scheme of nitric oxide reactions was correct, the spontaneous ignition temperatures of the different mixtures would vary widely. To test this, the spontaneous ignition temperatures were measured in a platinum furnace that could be heated up to 1,500° C. The expected differences were observed and lend weight to the postulated reaction scheme:

Fuel-oxidizer	Mixture strength	Spontaneous ignition temperature, ° C.	Remarks
NH_3-NO..	Stoichiometric	800	
C_2H_4-NO.	do	1,045	
CH_4-NO..	do	1,110	
H_2-NO...	do	1,320	
CO-NO...	Fuel lean	1,450	Stoichiometric mixture could not be ignited below 1,500° C.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1961 O - 581538

Generated on 2024-09-22 03:06 GMT / https://hdl.handle.net/2027/osu.32435030643316
Public Domain, Google-digitized / http://www.hathitrust.org/access_use#pd-google
Digitized by Google
Original from THE OHIO STATE UNIVERSITY